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NRL REPORT NO. R-3258

FR-3258

THE SERIES PEAKING TRANSFORMER

A CURRENT-ZERO TRIGGER SOURCE

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Approved by:

Dr. R. C. Guthrie, Head, Search Radar Section
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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH

Problem No. 39R02-22 March 16, 1948

NAVAL RESEARCH LABORATORY
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WASHINGTON, D.C.

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CONTENTS

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ABSTRACT

This report contains a discussion of the theory of a series peaking transformer, the derivation of design equations, considerations in the practical design work, and the manufacture of the transformer core from insulating and winding through heat treating. Finally, there is given a discussion on the use of the transformer with illustrating examples.

AUTHORIZATION

This work has been authorized in response to a request by the Bureau of Ships, BuShips ltr. S-S67-5, S-916-004113 of 25 October 1945 to Director, NRL. Problem S1225 (39R02-22) Very Long Range Search Radar.

PROBLEM STATUS

This is an interim report on this problem. Work is continuing.

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THE SERIES PEAKING TRANSFORMER

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INTRODUCTION

The series peaking transformer is a device which furnishes no voltage at exciting-current amplitudes beyond a critical value. Voltages near current-zero points are obtained if the rate of current change at current-zero is finite. The current-zero series peaking transformer met the requirement for a dependable trigger source for the hydrogen-thyratron switch tube in the model pulse modulator for the radar being developed under problem number S1225, and it was because of this need that the peaking transformer work was done. The series peaking transformer conceivably has many other uses. Therefore, it was considered profitable to write a report giving general design and constructional information for the manufacture of a series peaking transformer.

DERIVATION OF THE TRANSFORMER DESIGN EQUATIONS

If the inductance of a coil can be reduced to practically zero by making its magnetic circuit become saturated at any current greater than some predetermined small value, then the induced voltage will be zero at all times except when the current is less than this value; further, there will be an induced voltage when the current, during the time of small value, has a finite rate of change. This is the principle of the series peaking transformer.

The transformer must be designed to develop the required voltage during the unsaturated period. From a knowledge of the given current wave form, the rate of change of this current in the vicinity of the current-zero points may be determined. The transformer primary inductance is related to the voltage which must be induced across it and the derivative of the exciting current by the equation,

$$\nu = L \frac{di}{dt} \qquad (1)$$

where ν = instantaneous potential in volts,
L = inductance in henries,
i = current in amperes,
t = time in seconds.

But,

$$L = \frac{0.4\pi N^2 \mu A \times 10^{-8}}{l} \text{ henries,} \qquad (2)$$

where L = inductance in henries,
N = turns of copper winding,
μ = permeability of the core material,

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A = cross-sectional core area in cm^2,
l = mean magnetic path length in cm,

so,
$$\nu = \frac{0.4\pi N^2 \mu \; A \times 10^{-8}}{l} \frac{di}{dt} . \tag{3}$$

The pulse width from the peaking transformer is determined by the time relative to the time of current-zero at which saturation takes place. The value of the magnetizing intensity which causes saturation of the magnetic core may be determined from the characteristic curves of the core material. The value of current corresponding to the instant at which saturation must occur may be determined from knowledge of the current waveform. These two quantities are related by the following equation,

$$H_S = \frac{0.4\pi \, N i_S}{l} , \tag{4}$$

where N = turns of copper wire,
i_S = current in amperes at which the core must saturate,
l = mean magnetic path length in cm,
H_S = magnetizing force in Oersteds producing core saturation.

Equations (3) and (4) satisfy two different requirements which must be met simultaneously in the transformer. There are three unknown quantities N, A, and l. By choosing one arbitrarily, the other two may be found.

It is usually better to choose l. It is the parameter which physically limits the construction of the transformer as it, most of all, regulates the space allowed for the copper winding.

Solving for N in equation (4), one obtains

$$N = \frac{H_S \, l}{0.4\pi \, i_S} . \tag{5}$$

Then, this value of N may be substituted in equation (3) so that

$$A = \frac{0.4\pi \, i_S^{\,2} \, \nu \times 10^8}{(H_S)^2 \, \mu l \frac{di}{dt}} . \tag{6}$$

By choosing l as some physically convenient value, A and N can be found which satisfy both requirements of pulse-width and pulse-amplitude.

It is possible to arrive at values for A, N, and l which, although they satisfy the equations, may be impractical to incorporate in the manufacture. If subsequent choices of arbitrary values of l show that it is physically impractical to manufacture the transformer, a change in pulse voltage, pulse width or both must be tolerated.

PRACTICAL DESIGN CONSIDERATION

The best choice of a magnetic core material is one whose characteristics are such that: (1) the saturation level occurs very abruptly, as seen in an acute knee of its B-H curve, (2) the permeability is very high, and (3) the core saturates at very low values of magnetizing force. Unfortunately, present magnetic core materials are far from having ideal characteristics. Two materials which rank among the best available are Allegheny Ludlum 4750 and Allegheny Mumetal. From equation (3) it is seen that, if everthing else

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remains the same, an increase in μ gives an increase in ν. Also, if saturation occurs abruptly so that $d\phi/dt$ becomes zero with very little time during transition, the pulse voltage output can be made to break sharply at the base.

In order that the maximum magnetic permeability may be realized, the core should have a minimum of air gap. By the equation below, the effect of an air gap on the working permeability of the magnetic circuit can be seen.

$$\mu_d = \frac{\mu_m}{1 + \mu_m \times \frac{a}{l}}, \tag{7}$$

where μ_d = working permeability,
μ_m = inherent permeability of the material,
a = air gap length,
l = mean magnetic path length in core in same units as a.

To reduce the effective air gap to a minimum requires that the core be of the continuously wound type. More will be said about the core manufacture later.

In the design equations, losses in the core material were not considered because in most cases they are negligible.

When the transformer is used under a loaded condition, one can expect the pulse voltage to be reduced and the pulse width may be increased from the calculated design values. In the case of a constant-current generator supplying the transformer, the voltage will drop in amplitude since there will be no additional current available to supply needed magnetizing current to keep the voltage constant. Pulse-width will increase because the magnetizing force will decrease and core saturation will occur at a time farther removed from current zero on the exciting-current wave. Leakage inductance should also be considered since it will cause a drop in pulse-voltage amplitude. With a constant-voltage generator, the generator current can vary to compensate for the extra magnetizing current needed and the pulse voltage and width will remain fixed except for changes due to internal impedance of the transformer.

A sample design of a series-peaking transformer may be helpful in understanding the problem. It is assumed that Allegheny Ludlum 4750 core material is used and that the required pulse voltage is 300 and pulse width is 200 microseconds. A current, $i = 1.0 \sin 377t$, will be chosen as a sample current. The shape of the pulse will be required to be reasonably rectangular.

Since the pulse width is 200 microseconds, the current at which core saturation takes place must be the value at 100 microseconds each side of current zero or

$$i_s = 1.0 \sin \omega t_s = 0.0377 \text{ amperes},$$

where i_s = current at t_s,
t_s = time from current-zero reference point equal to one-half required pulse width or 100 microseconds.

The rate of change of current at zero current is

$$\left.\frac{di}{dt}\right]_{i=o} = \left.\frac{d\,(1.0 \sin \omega t)}{dt}\right]_{i=o} = 377 \text{ amp/sec.}$$

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This rate of change of current holds substantially constant over the time required for the pulse, thus the pulse will be flat on top if the B-H curve of the core material is linear over the unsaturated range. From equation (5),

$$N = \frac{H_s l}{0.4\pi i_s} = 169 \text{ turns},$$

if 0.8 Oersted is the magnetizing force at which core saturation occurs, as determined from the characteristic curves of the core material and 10 cm is the chosen magnetic path length (approximately equal to the mean circumference of the core). From equation (6),

$$A = \frac{0.4\pi (i_s)^2 \nu \times 10^8}{(H_s)^2 \mu l \frac{di}{dt}} = .444 \text{ cm}^2.$$

Thus N and A have been determined from a value of l, and all three are practical dimensions.

CORE PROCESSING

The magnetic tape as purchased from the manufacturer comes uninsulated and non-annealed, therefore the core fabrication must include insulation and annealing. All the mechanical operations in the core fabrication must be done before annealing, as any bending, tearing, or jarring of the material after annealing will alter its molecular arrangement and magnetic characteristics.

In the core manufacture, the tape may be drawn through a bath of insulating solution, passed through a hot air drier, and the desired number of layers wound onto a circular steel mandrel and clamped by a steel clamp with steel bolts. The mandrel, clamp, and bolts are steel because of its stability under the heat treating or annealing process.

The tape is insulated to reduce eddy current paths. The problem of insulating reduces to one of using an insulating material which will not deteriorate under the high temperatures used for annealing. Magnesium oxide provides a good insulation although some silicate compounds can also be used. The magnesium oxide is mixed with carbon tetrachloride to form the bath solution. Ten grams of magnesium oxide and 1 gram of Aerosol are added to about 50 milli-liters of carbon tetrachloride. The Aerosol acts merely as a wetting agent for the solution. If an electric potential is applied between the tape and the bath container so that the tape is negative and the container positive, the insulation will be applied more evenly and speedily. Experiments showed that when the migration current caused by the potential difference is about three milliamperes for one-half-inch-wide tape running at the rate of about ten inches per minute through a solution path about four inches in length, the insulation thickness will be approximately 0.0015 inch. For tape of 0.003 inch in thickness, this insulation thickness gives a packing factor of 50 percent. The packing factor is the ratio of total actual iron cross-sectional area to total cross-sectional area of the core. This factor is to be considered in the physical limitations of the core design since actual core cross-sectional area will not be apparent cross-sectional area.

After the insulation is applied and the tape emerges from the bath, hot air may be blown on the tape for rapid drying of the solution. Rapid drying tends to reduce the solution-running and thus the coating is held more uniform.

The ribbon is wound onto a steel mandrel and clamped in place after the prescribed number of laminations is applied. The core is then ready for the annealing process.

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Fig. 1 - Front View of Experimental Core Winding Machine

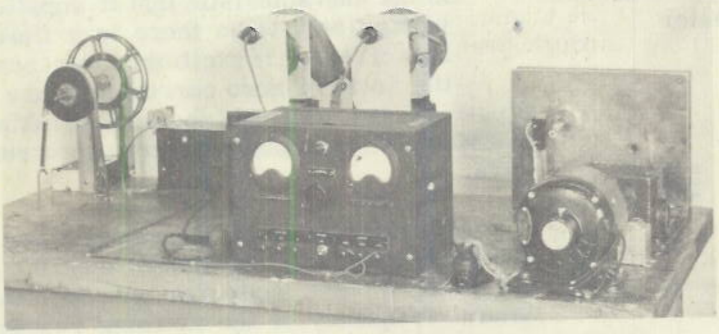

Fig. 2 - Rear View of Experimental Core Winding Machine

Figure 1 shows a satisfactory experimental core manufacturing machine showing, from right to left, the supply reel, insulating bath container, hot-air driers and winding mechanism with the tape being wound onto the mandrel. Figure 2 shows the reverse side of the core manufacturing machine and a view of the d-c power supply, the motor drive, and the turns counter.

Core manufacture need not necessarily consist of a winding operation. The core may be made of a required number of washer type laminations stamped from sheets of the magnetic material. The insulation requirements are the same, but the continuous operation of the core manufacture is not so easily achieved.

Heat treatment or annealing is done in a bath of pure hydrogen to eliminate any oxidation that might take place. The core is enclosed in a leak-proof welded container with openings only for dried hydrogen to enter and exit. The core is heated to about 1121°C and held at that temperature for four hours. After this time, it is cooled to about 593°C at a rate not to exceed 37.7°C per hour. The cooling rate beyond this point is unimportant. An alternative method in the annealing process is to remove the steel mandrel and clamp before final heat treatment so that its presence cannot add to the contamination of the hydrogen in the hydrogen bath. The core and clamp can be given what is known as a "hold" or "set" anneal. This constitutes bringing the charge up to a temperature of about 900°C and holding it at this temperature for about an hour. After this operation has been completed, the clamp and mandrel may be removed and the core will retain its shape. The final heat treatment may then proceed as previously described.

MAKING THE TRANSFORMER

The techniques of toroidal transformer winding may be found in various reference books. It should be kept in mind that it is advantageous to wind the copper coils so that there will be a minimum of distributed capacity and leakage inductance if the characteristics of the output pulse are to be reasonably close to the characteristics sought in the design. Some type of protective covering should be applied to the core before the copper winding is installed. This cover may be in the form of a thick coating of glyptal which is put on by a successive dipping and drying process, or a bakelite doughnut shaped trough may hold the core. The winding of the copper may be done by a toroidal-winding machine or with a hand manipulated bobbin.

Fig. 3 - Actual Series Peaking Transformer Used in Model Modulator

Figure 3 shows a photograph of a series peaking transformer used to supply a trigger voltage to a 5C22 hydrogen-thyratron in the model modulator.

USING THE TRANSFORMER

The sole criterion for determining the application of a series peaking-transformer to a particular problem is the characteristic that it supplies voltage only when there is a finite rate of change in exciting current near the value of zero current. Figure 4 illustrates that quality of the series peaking transformer for an assumed exciting current wave.

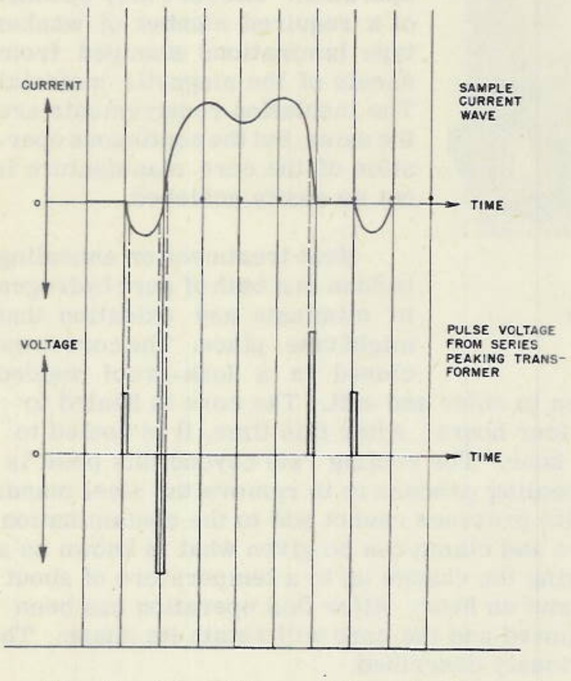

Fig. 4 - Wave Form of Sample Current Showing Corresponding Series Peaking Transformer Voltage Pulses

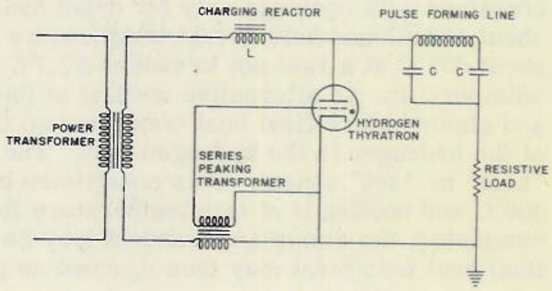

Fig. 5 - a-c Charging Pulse Modulator Circuit

One system in which the peaking transformer may be used advantageously is the a-c-charged pulse modulator, provided the natural frequency of the charging reactor and pulse-forming-line capacity is equal to or lower than the frequency of the charging supply voltage. Figure 5 shows a typical circuit of an a-c-charged pulse modulator. The voltage and current waves charging the total capacity of the pulse forming line, and the output voltage pulses from the peaking transformer excited by the same current wave are shown in Figure 6. Figures 7 and 8, respectively, show actual photographs of the voltage on the pulse forming network capacitors and the corresponding series-peaking-transformer voltage. (Examination of Figure 8 shows that the series-peaking-transformer pulse contains a downward spike-like voltage. This reversed spike is a transient caused by the discharge of the pulse-forming line.)

Precautionary steps must be taken to prevent the resonant frequency of the charging inductance and the capacity of the pulse-forming line from ever becoming higher than the

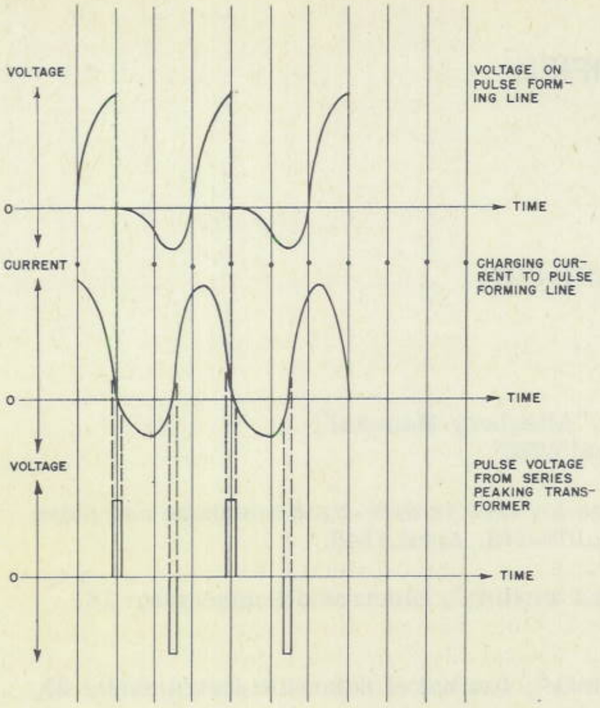

Fig. 6 - Wave Forms and Time Relationships of P.F.L. Voltage, Current, and Peaking Transformer Pulse Voltage where $f_{LC} \leq f_{\text{power supply}}$

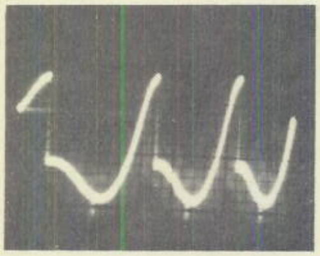

Fig. 7 - Actual Photograph of Voltage Wave on Pulse Forming Line Capacitors

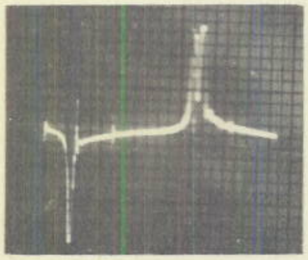

Fig. 8 - Actual Photograph of Voltage Pulse from Peaking Transformer

frequency of the charging-supply voltage as may be the case where the charging inductance may decrease appreciably under full load. If the charging network frequency should become high, the condition illustrated in Figure 9 will occur where the charging current reversal causes two additional series-peaking-transformer pulses. The negative pulse will not affect the operation of the modulator but the additional positive pulse will trigger the hydrogen-thyratron. If the pulse-forming line has appreciable voltage on it at that time, an extra modulator output pulse will occur and the modulator will not operate in the intended fashion.

Although the operation of an a-c charged pulse modulator is satisfactory when its charging network resonant frequency is higher than that of the charging supply voltage, that method of operation should not be used when the series-peaking transformer serves as the trigger source.

* * *

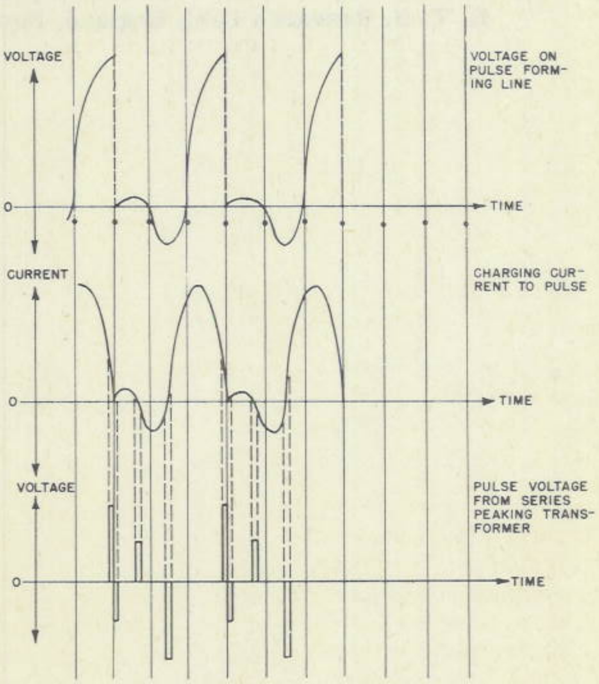

Fig. 9 - Wave Forms and Time Relationships of P.F.L. Voltage, Current, and Peaking Transformer Pulse Voltage where $f_{LC} > f_{\text{power supply}}$

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